B mixing and lifetimes at the Tevatron

FPCP 2006
Vancouver

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on behalf of the DØ and CDF Collaborations

Outline

THIS TALK

- Precision *B* Lifetimes
  - motivation
  - Λ_b
  - B_s
  - B_s lifetime difference
- *B* Mixing
  - current status
  - ingredients
  - results
- Summary

OTHER TALKS

- CDF and D∅ detectors

  CDF and D∅ Hot Topics
- Detailed B_s mixing at D∅

  D. Buchholz

  D∅ Hot Topics
- Detailed $B \to hh$

  D. Tonelli

  CDF Hot Topics
- B_c lifetime

  I. Kravchenko

  B Spectroscopy
- $B_s \to D_s D_s$

  R. Van Kooten

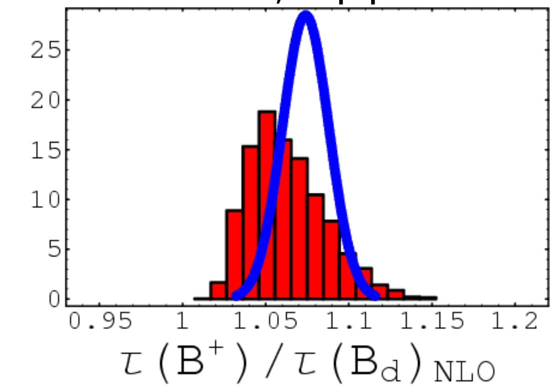
  Bs Decays and *B* leptonic decays

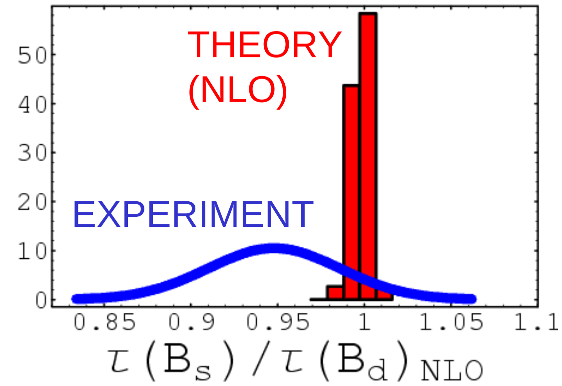
Precision *B* Lifetimes

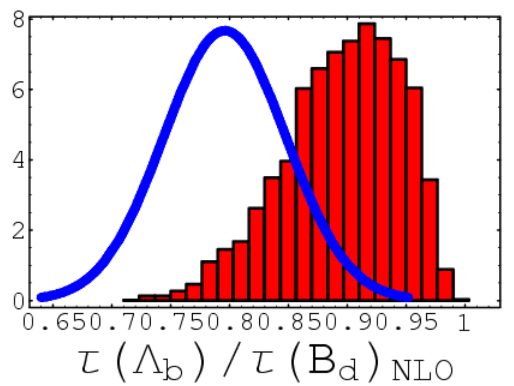
Motivation

- *b*-hadron decays dominated by *b*-quark
- Light quarks are included with $1/m_b$ perturbative expansions (HQE)
  - expect small differences between lifetimes of different species
  - lifetime ratios reduce theory uncertainties

C. Tarantino, hep-ph/0310241





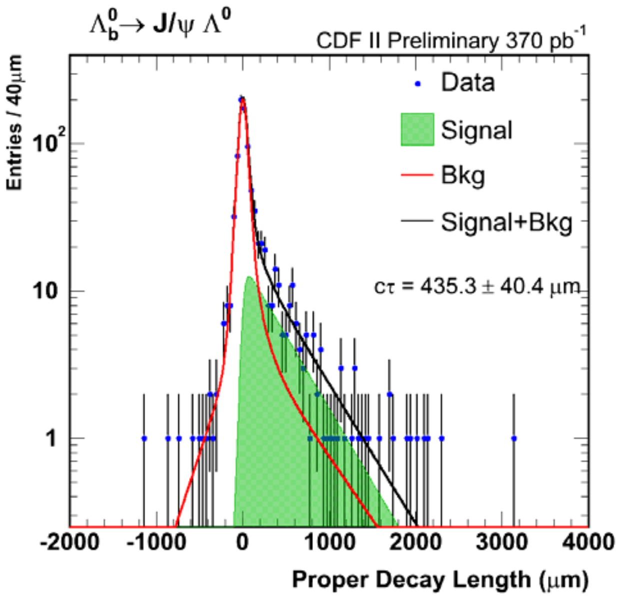


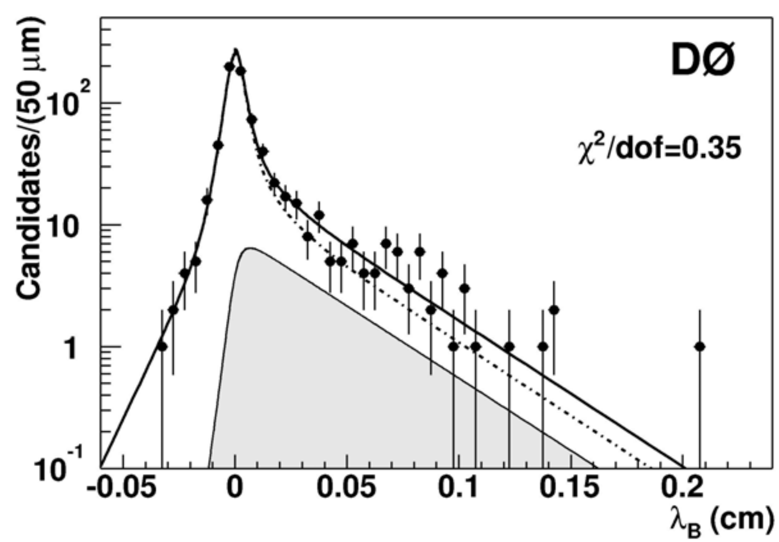
Λ_b Lifetime

- CDF and DØ have measured $\Lambda_b \to J/\psi\ \Lambda$ lifetime
- Better proper time resolution than $\Lambda_b \to \Lambda_c\ l\nu$ *(world average dominated)*
- Earlier $\tau(\Lambda_b)/\tau(B^0)$ predictions were 2σ above experiment
  - new calculations including higher order effects predict lower ratio

CDF *370 pb⁻¹*	DØ *250 pb⁻¹*
$\tau_{\Lambda_b} = 1.45^{+0.14}_{-0.13}\,(stat) \pm 0.02\,(syst)\,\mathrm{ps}$	$\tau_{\Lambda_b} = 1.22^{+0.22}_{-0.18}\,(stat) \pm 0.04\,(syst)\,\mathrm{ps}$

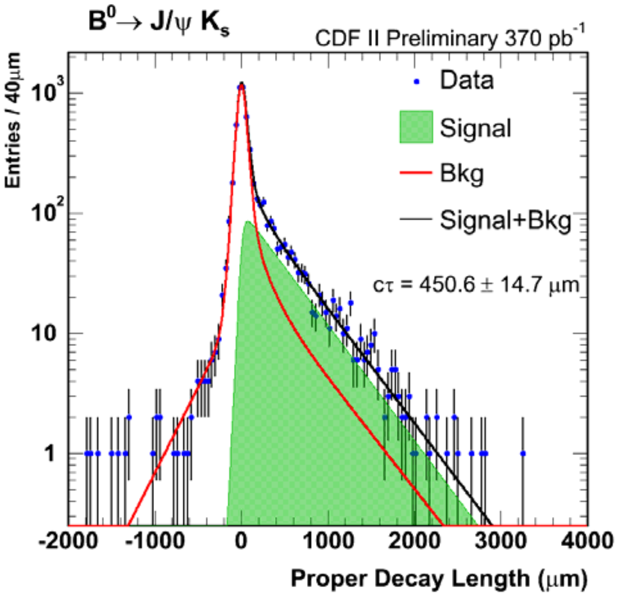
PRL 94 102001 (2005)





Λ_b Lifetime at CDF

- Analysis based upon 370 pb^{-1}
- Technique
  - unbinned maximum likelihood fit to proper decay-length and mass
- $\Lambda_b \to J/\psi\, \Lambda^0$ 194 $\pm$ 23 candidates
  - $J/\psi \to \mu\mu$
  - $\Lambda^0 \to p\pi^-$
- Use B^0 reference mode
  - larger yield and similar decay topology
- $B^0 \to Jpsi\, K_s^0$ 1225 $\pm$ 53 candidates
  - $J/\psi \to \mu\mu$
  - $K_s^0 \to \pi^+\pi^-$

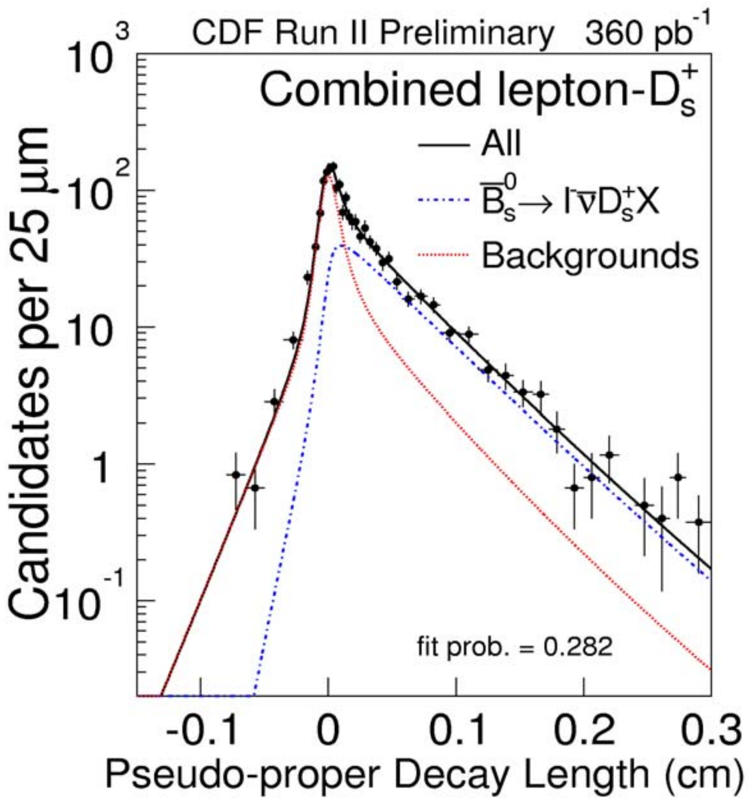


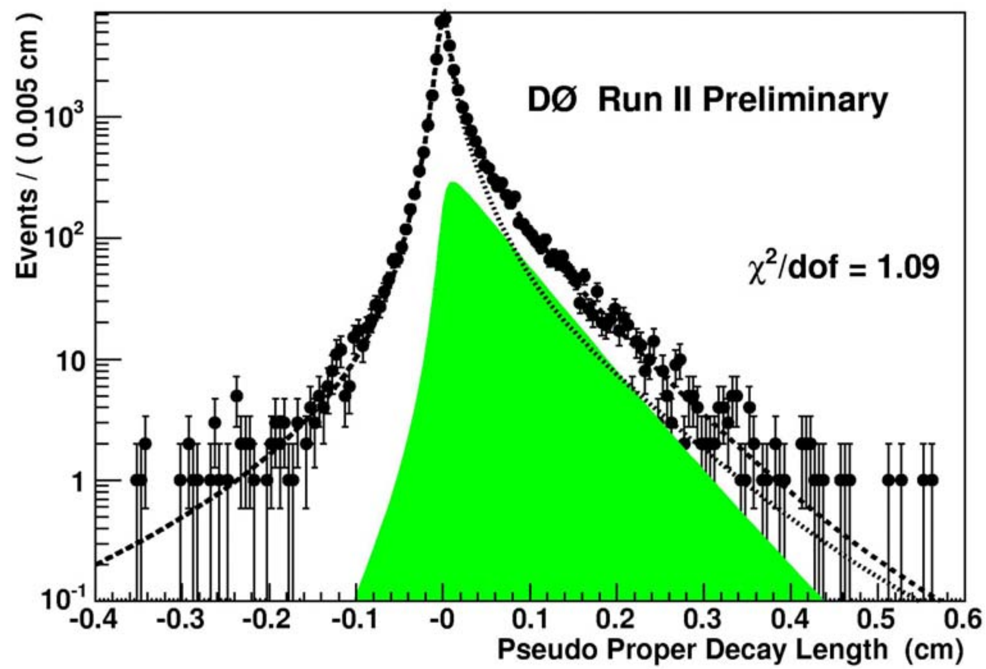
CDF 370 pb^{-1} $\tau_{B^0} = 1.503^{+0.050}_{-0.048}\,(stat) \pm 0.016\,(syst)\,\mathrm{ps}$

HFAG $\tau_{B^0} = 1.527 \pm 0.008\,\mathrm{ps}$

B_s Lifetime

- DØ and CDF measure B_s^0 lifetime in $B_s^0 \to D_s^- l^+ \nu\, X$





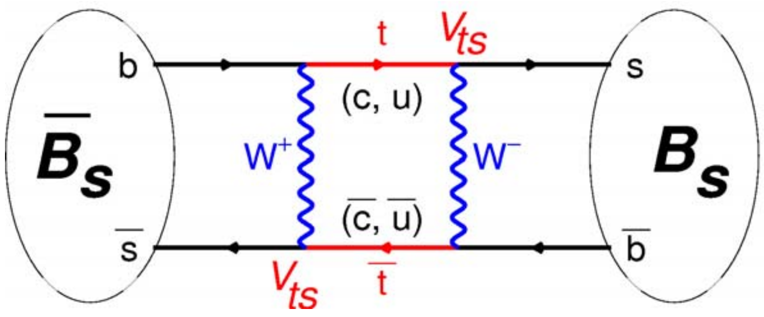
CDF *360 pb^{-1}* | DØ *400 pb^{-1}*

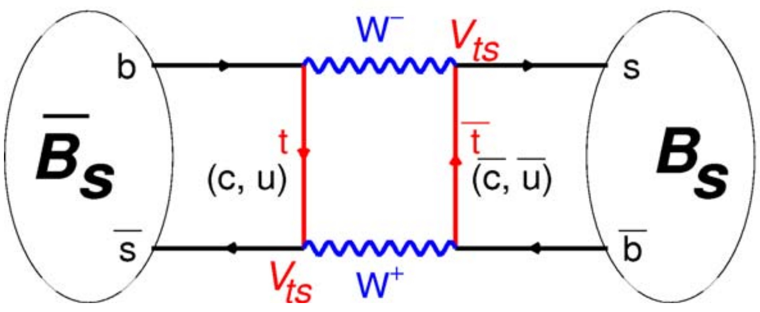
$$\tau_{B_s^0} = 1.381 \pm 0.055\,(stat)^{+0.052}_{-0.046}\,(syst)\,\mathrm{ps}$$

$$\tau_{B_s^0} = 1.420 \pm 0.043\,(stat) \pm 0.057\,(syst)\,\mathrm{ps}$$

best in the world

Neutral Meson Mixing





- Quark mixing ⇒ non-diagonal Hamiltonian for $\langle \overline{B} \,|\, H \,|\, B \rangle$

$$H = \begin{pmatrix} M & M_{12} \\ M_{12}^{*} & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^{*} & \Gamma \end{pmatrix}$$

- Diagonalizing the Hamiltonian results in
  - two eigenstates $\left| B_s^{Heavy} \right\rangle$ and $\left| B_s^{Light} \right\rangle$
  - two masses m_H and m_L, with $\Delta m \equiv m_H - m_L$
  - two decay widths Γ_H and Γ_L, with $\Delta\Gamma \equiv \Gamma_L - \Gamma_H$

R. Van Kooten
B_s decays and B leptonic decays

B_s Lifetime Difference

- $B_s \to J/\psi\ \phi$

Pseudoscalar $\to$ Vector - Vector

- Decay amplitude decomposed into 3 linear polarization states
  - A_0 = S + D wave $\Rightarrow$ P even
  - $A_{||}$ = S + D wave $\Rightarrow$ P even
  - $A_\perp$ = P wave $\Rightarrow$ P odd
- If CP violation neglected
  - $B_{s,\text{Light}} \approx$ CP even
  - $B_{s,\text{Heavy}} \approx$ CP odd
  - angular distributions are different
- Angular analysis separates CP eigenstates $\Rightarrow$ measure two lifetimes

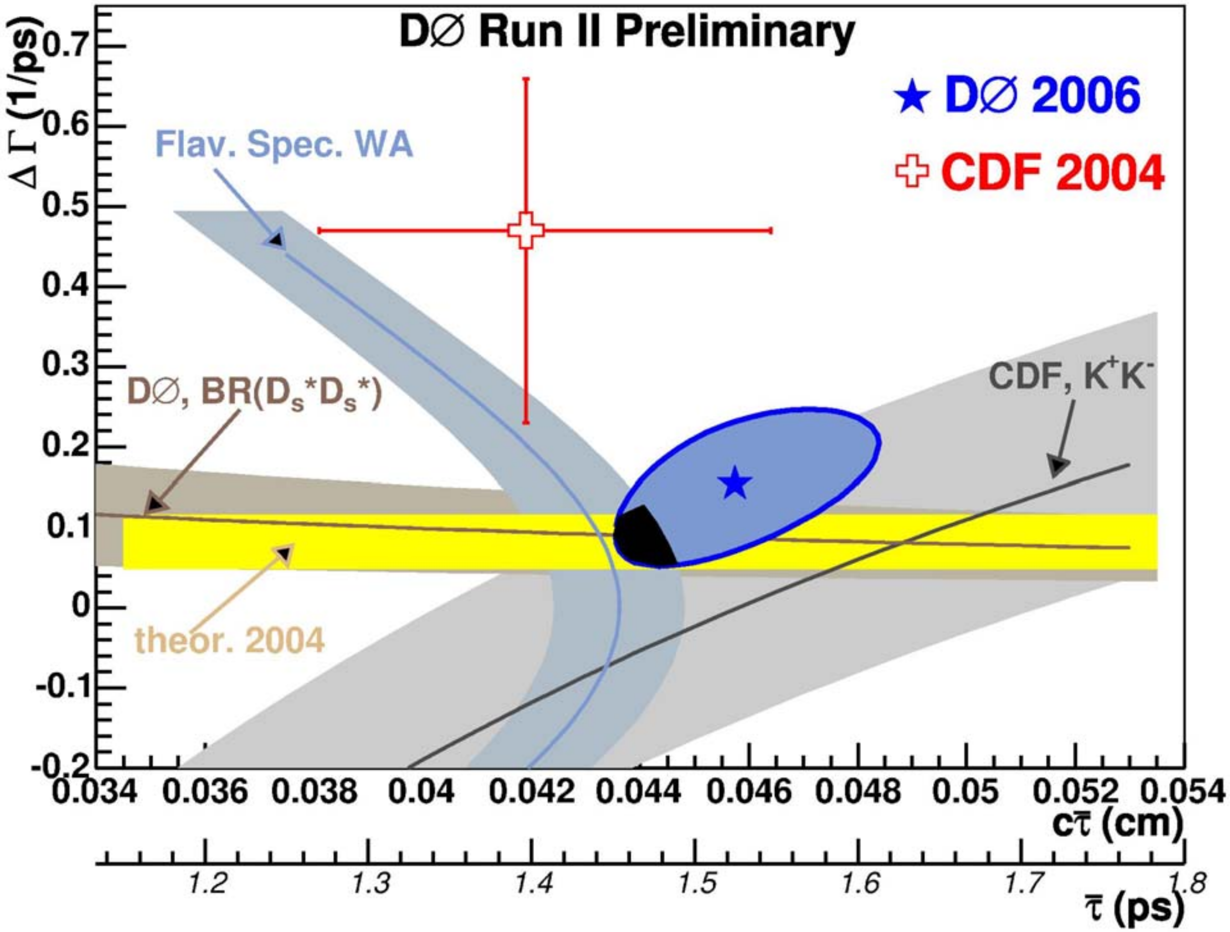
B_s Lifetime Difference

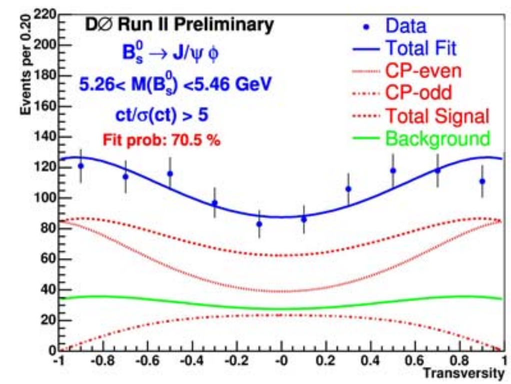
CDF *260 pb^{-1}*

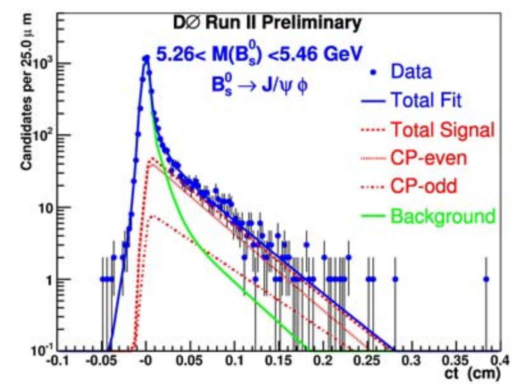
$$\Delta\Gamma = 0.47^{+0.19}_{-0.24}\,(\text{stat}) \pm 0.01\,(\text{syst})\,\text{ps}^{-1}$$

DØ *800 pb^{-1}*

$$\Delta\Gamma = 0.15 \pm 0.10\,(\text{stat})\,^{+0.03}_{-0.04}\,(\text{syst})\,\text{ps}^{-1}$$







$B_s \to K^+K^-$ and B_c

- First $\tau_{B_s \to K^+K^-} (\approx \tau_L)$ measurement (~95% CP even)

CDF *360 pb[-1]*

$$\tau_L = 1.53 \pm 0.18\,(stat) \pm 0.02\,(syst)\,\text{ps}$$

D. Tonelli
CDF Hot Topics

- Expected $\tau(B_u^+) \sim 3 \times \tau(B_c^+)$
- Lifetime extracted from $B_c^+ \to J/\psi e^+ \nu_e$ decay

CDF *360 pb[-1]*

$$\tau_{B_c^+} = 0.463^{+0.073}_{-0.065}\,(stat) \pm 0.036\,(syst)\,\text{ps}$$

best in the world

I. Kravchenko
B Spectroscopy

DØ *210 pb[-1]*

$$\tau_{B_c^+} = 0.448^{+0.123}_{-0.096}\,(stat) \pm 0.121\,(syst)\,\text{ps}$$

- B^+ and B^0 at LEP/SLC, *B* factories and Tevatron (CDF/D∅)
  - dominated by Belle and BaBar
- B_s dominated by Tevatron, LEP
- B_c at Tevatron
- Λ_b dominated by LEP, Tevatron

b-hadron species	measured lifetime [ps]	$\tau/\tau(B^0)$ lifetime ratio	predicted range
B^+	1.643 ± 0.010	1.076 ± 0.008	$1.04 - 1.08$
B_s *(→ flavor specific)*	1.454 ± 0.040	0.914 ± 0.030	$0.99 - 1.01$
Λ_b	1.288 ± 0.065	0.844 ± 0.043	$0.86 - 0.95$
B^0	1.527 ± 0.008	**hep-ex/0603003**	
B_c	0.469 ± 0.065	**March 2006**	

B Mixing

Theoretical Prediction

- SM prediction for the ratio of B_s and B^0 mixing frequencies

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2}$$

$$\xi^2 = 1.21 \pm 0.02^{+0.035}_{-0.014}$$

- Δm_d precisely measured

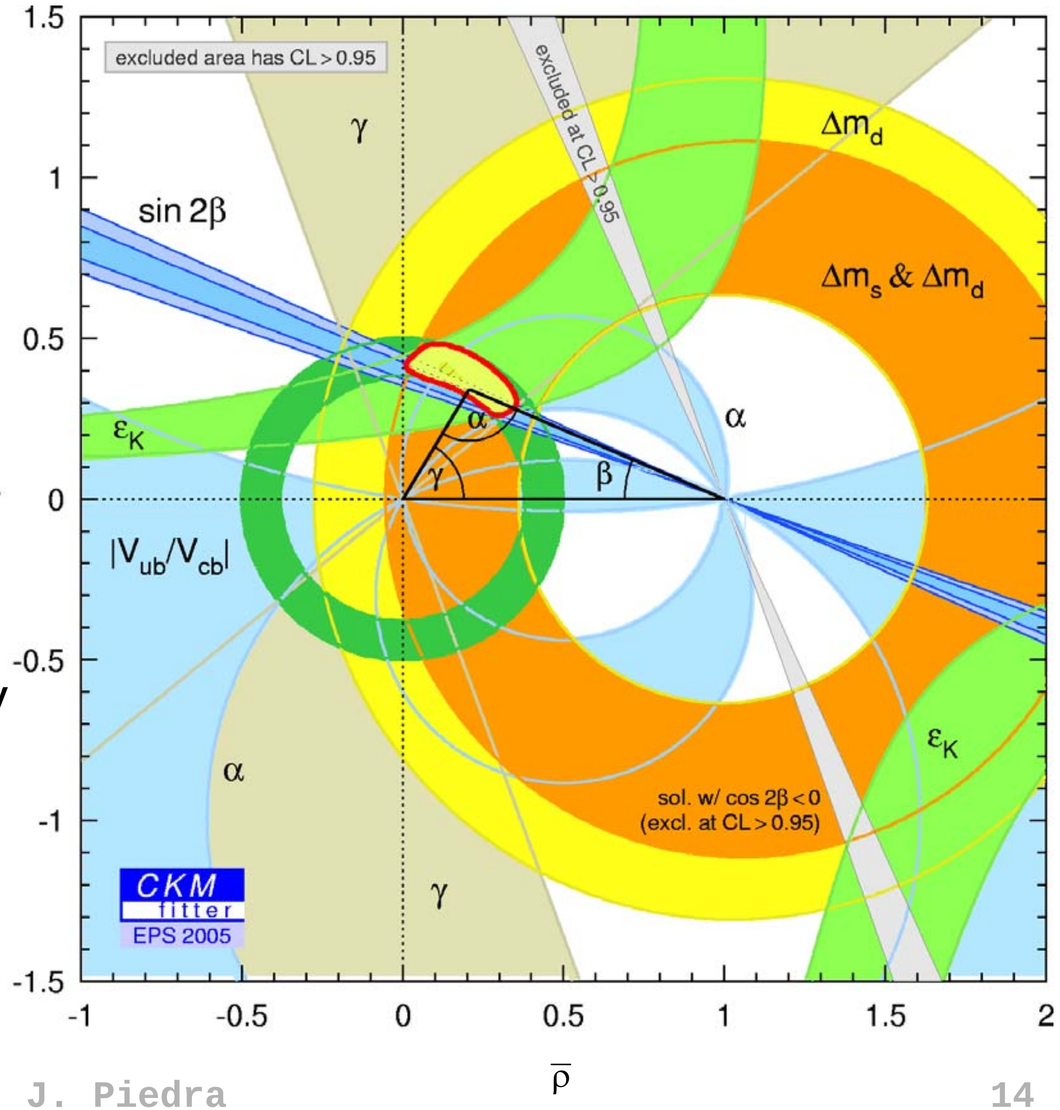
$$\Delta m_d = 0.508 \pm 0.004 \text{ ps}^{-1}$$

- Δm_s not yet measured precisely

CKM fit

$$\Delta m_s = 18.3^{+6.5}_{-1.5} \text{ ps}^{-1}$$

- Potential NP discovery



B Mixing Significance

$S \equiv$ signal candidates

$B \equiv$ background candidates

$\sigma_{ct} \equiv$ time resolution

$$significance \propto \sqrt{\frac{S}{S+B}}\sqrt{\frac{\varepsilon\mathcal{D}^2}{2}}e^{-\frac{1}{2}\sigma_{ct}^2\Delta m_s^2}$$

$$\varepsilon \equiv \frac{correct\ \ tags + incorrect\ \ tags}{N} \qquad \mathcal{D} \equiv \frac{correct\ \ tags - incorrect\ \ tags}{correct\ \ tags + incorrect\ \ tags}$$

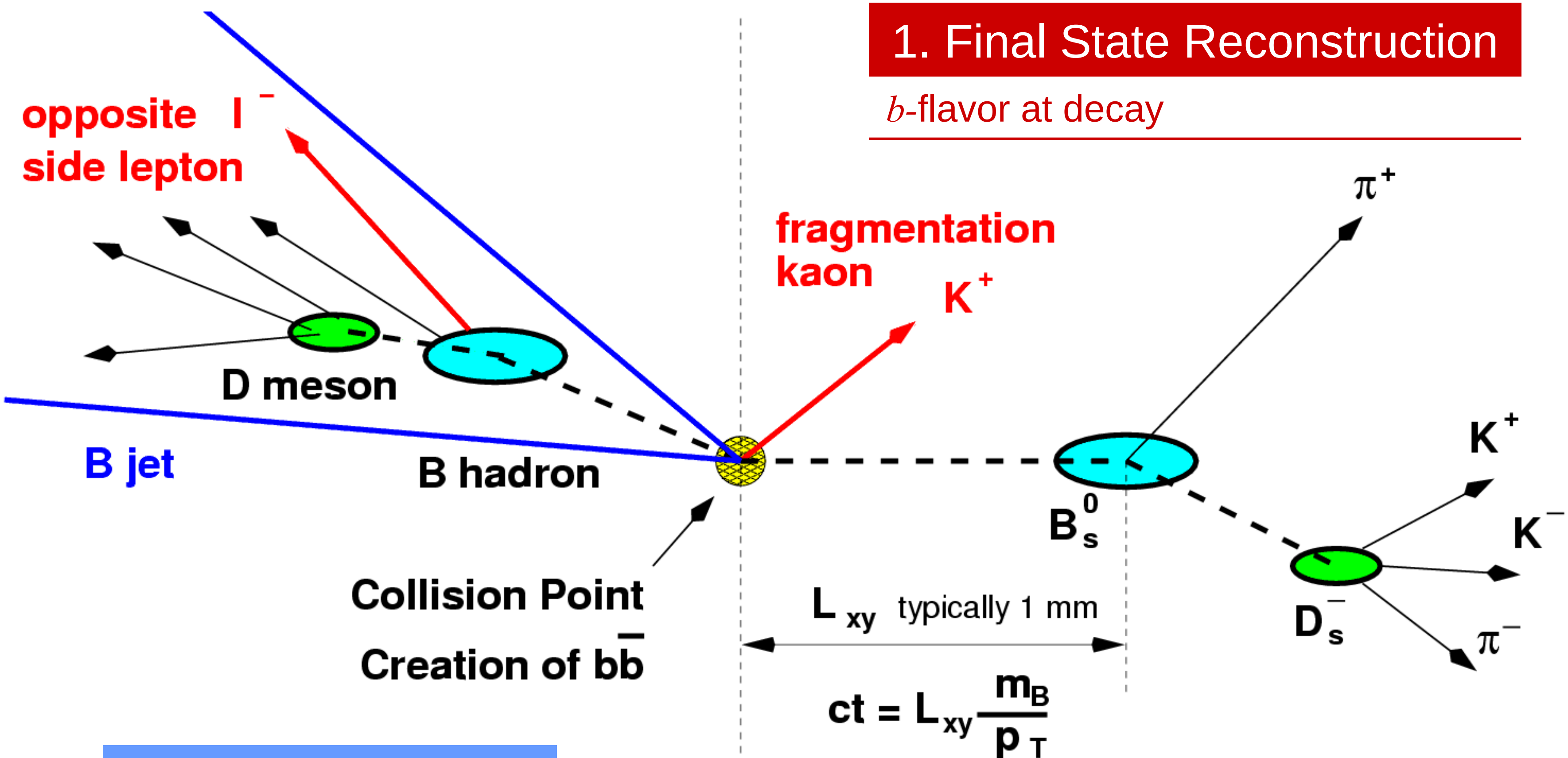
- The dilution $\mathcal{D}$ measures the purity, $\mathcal{D} = 0\ (1) \Rightarrow$ random (perfect) tagger
- The dilution attenuates the observed oscillations

$$P(t)_{B^0 \to B^0, \overline{B}^0} \cong \frac{1}{2\tau}e^{-\frac{t}{\tau}}\left[1 \pm \mathcal{D}\cos(\Delta m t)\right]$$

B Mixing Ingredients

1. Final State Reconstruction

b-flavor at decay



3. *b*-Flavor Tagging

b-flavor at production

2. Proper Decay Time

In *B* rest frame

4. Amplitude Scan for B_s Mixing

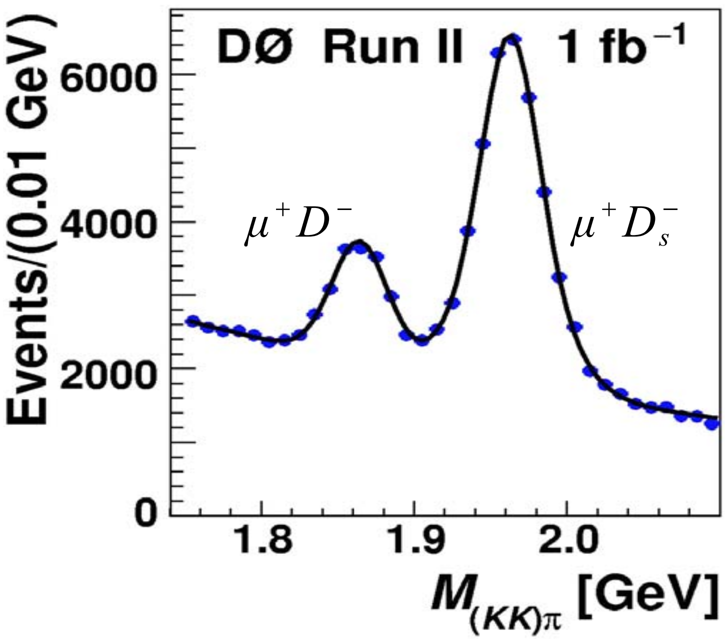
Set a lower limit or observe Δm_s

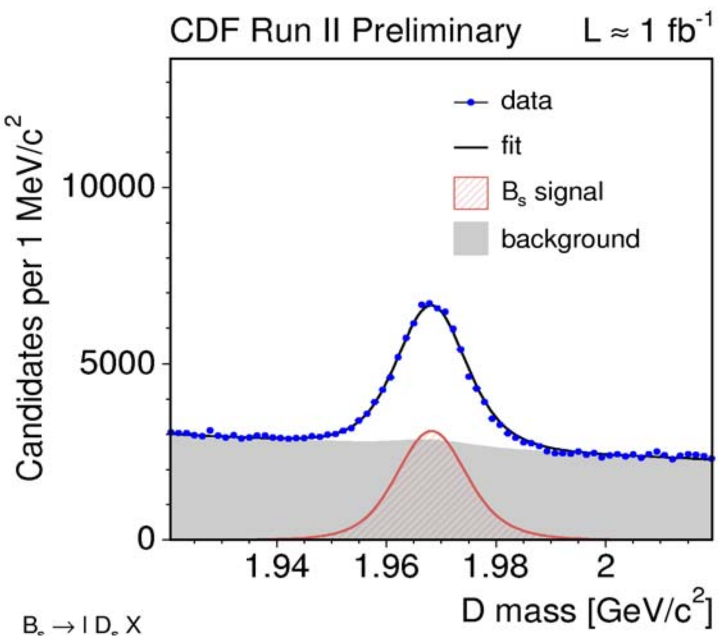
Opposite Side

Trigger Side

Reconstructed $B_s \to l^+ D_s^- X$

- DØ exploits semileptonic decays from μ trigger
- CDF uses both electrons and muons





DØ *1 fb^{-1}*

$$N_{\mu^+ D_s^-} = 26710 \pm 556\,(stat)$$

$$D_s^- \to \phi\pi^-, \phi \to K^+ K^-$$

CDF *1 fb^{-1}*

$$N_{l^+ D_s^-} \sim 53300$$

$$D_s^- \to \phi\pi^- / K^{*0} K^- / \pi^+\pi^-\pi^-$$

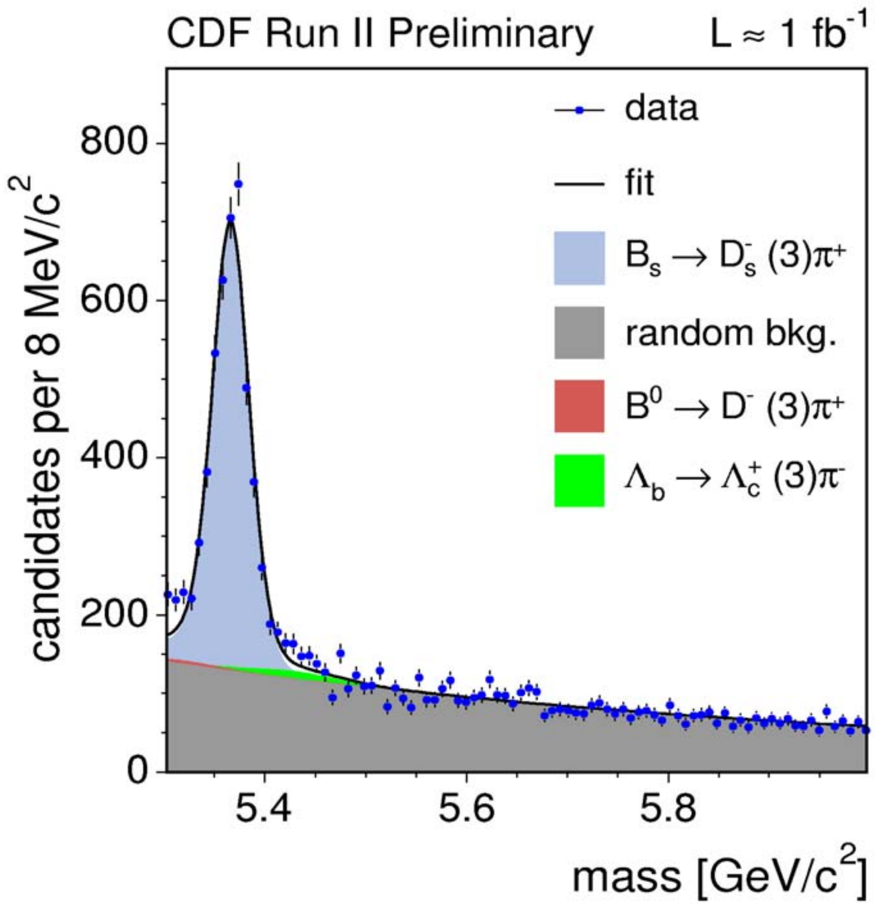
Reconstructed $D_s^-(\pi^+\pi^-)\pi^+$

- CDF collects hadronic *B* decays by triggering on impact parameter
- Around 3700 B_s signal candidates

$$B_s \to D_s^-(\pi^+\pi^-)\pi^+, D_s^- \to \phi\pi^-$$

$$B_s \to D_s^-(\pi^+\pi^-)\pi^+, D_s^- \to K^{*0}K^-$$

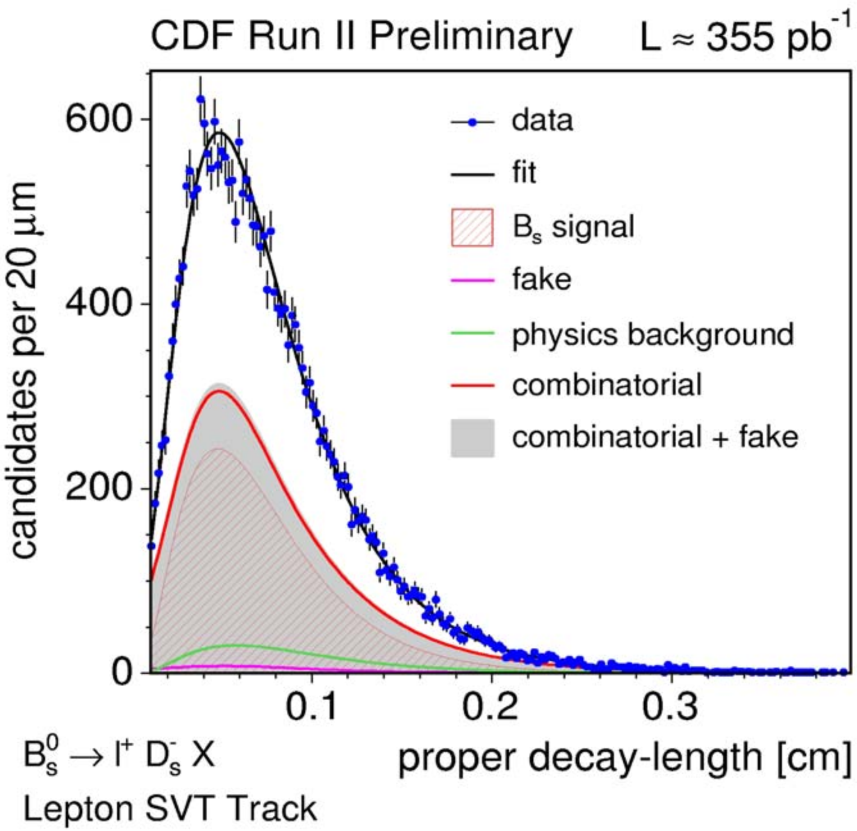
$$B_s \to D_s^-(\pi^+\pi^-)\pi^+, D_s^- \to \pi^+\pi^-\pi^-$$



Proper Decay Time

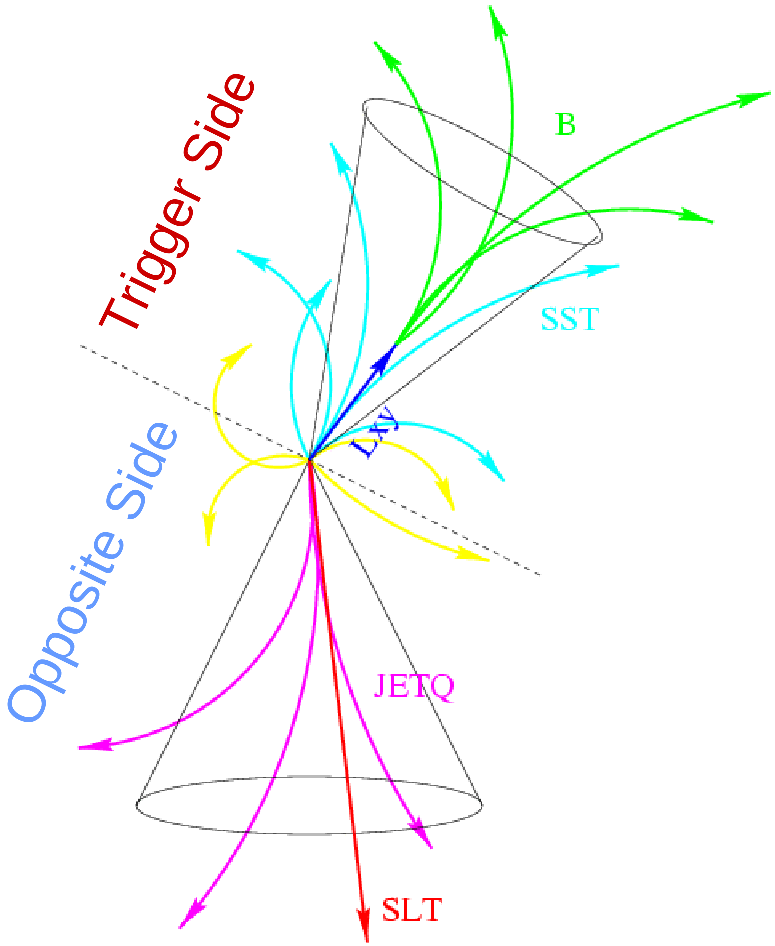
- Procedure
  - measure p_T of *B* daughter tracks
  - measure the decay length L_{xy}
  - boost *B* back to its rest frame
- Fully reconstructed decays
  - all daughters reconstructed
- Partially reconstructed decays
  - some tracks escape detection

$\Rightarrow$ need simulation



b-Flavor Tagging

- A flavor tagger determines the b-flavor at production time
- $b\bar{b}$ production $\Rightarrow$ flavor tagging on the Trigger Side or the Opposite Side

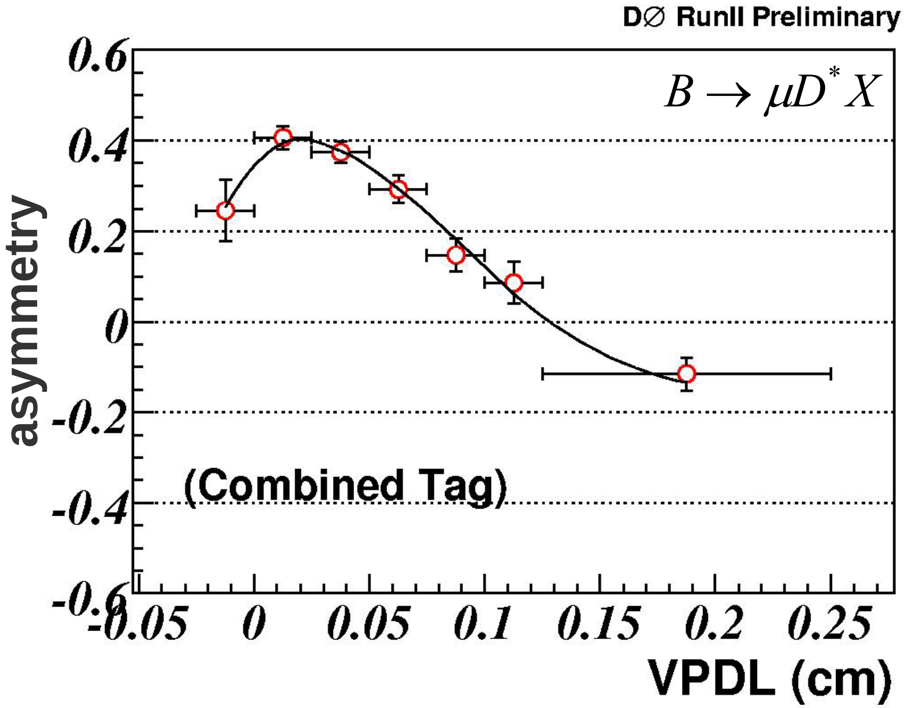


- Soft Lepton Tagger **SLT**
  - look for $B \to l\nu DX$ decay on the OS
  - lepton charge indicates b-flavor
- Jet Charge Tagger **JQT**
  - look for jet or secondary vertex from OS
  - jet charge indicates b-flavor
- Same Side (Kaon) Tagger **SS(K)T**
  - look for a fragmentation track on the TS
  - it is charge correlated with the b-flavor

Flavor Analysis on B^+ and B^0

- Calibrate opposite side flavor taggers prior to Δm_s analysis
  - combine several $B^{+,0}$ decays
  - combine all taggers
- Direct Δm_d measurement
  - cross-check for B_s mixing

combined $\varepsilon\mathcal{D}^2$ (%)	
DØ	CDF
2.48 ± 0.22	1.55 ± 0.08



DØ semileptonic *1 fb^{-1}*	Δm_d = 0.506 ± 0.020 (stat) ± 0.016 (syst) ps^{-1}
CDF semileptonic *1 fb^{-1}*	Δm_d = 0.509 ± 0.010 (stat) ± 0.016 (syst) ps^{-1}
CDF hadronic *355 pb^{-1}*	Δm_d = 0.536 ± 0.028 (stat) ± 0.006 (syst) ps^{-1}
world average	Δm_d = 0.508 ± 0.004 ps^{-1}

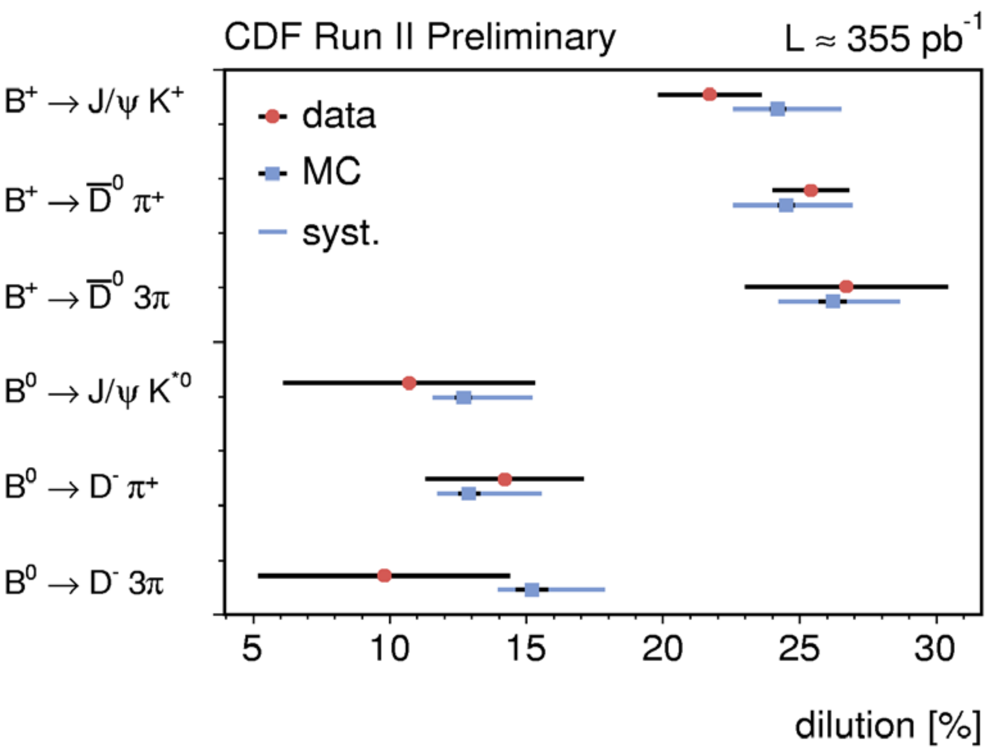
B Mixing SSKT at CDF

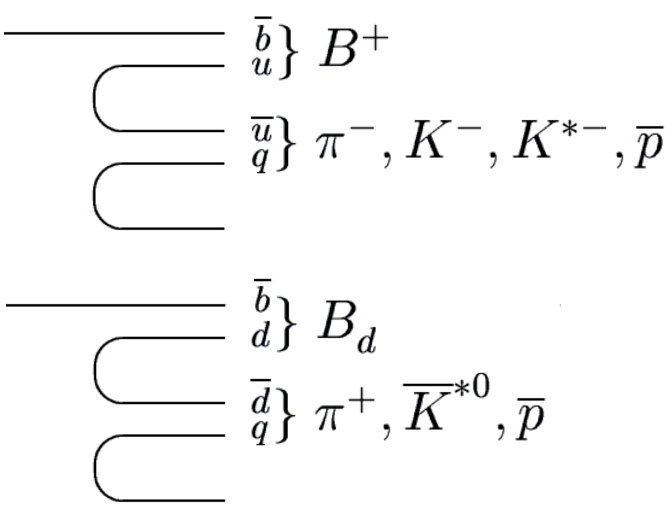
- Look for the fragmentation track that is charge correlated with the *B*
- Δm_s not yet measured precisely

⇒ Parameterization from MC

- Extensive data/MC comparisons on all tagging related quantities

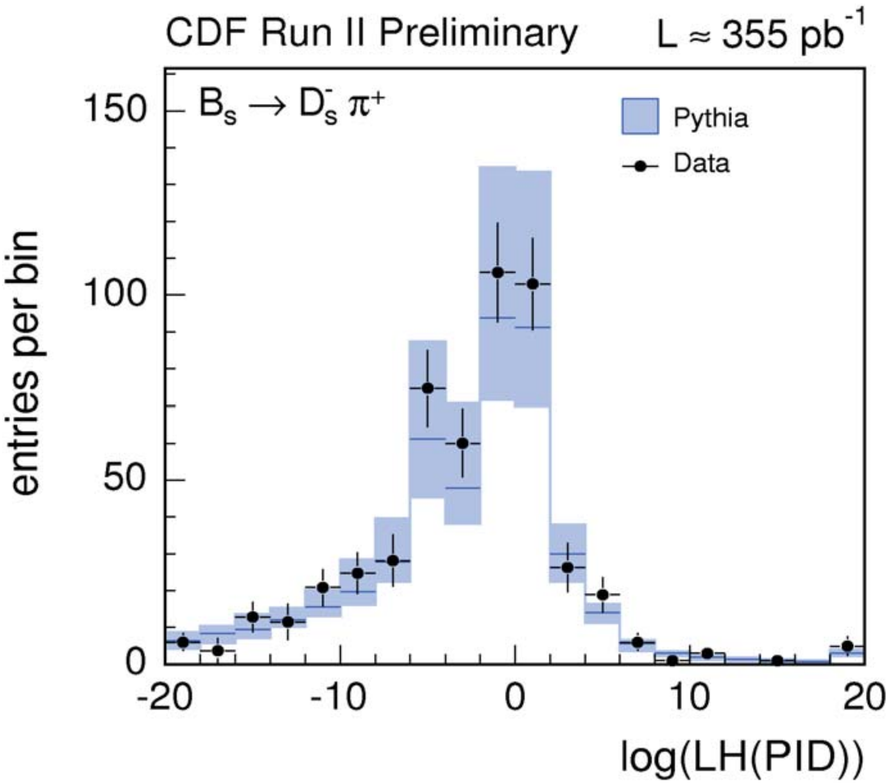
⇒ Rely on MC prediction of SSKT performance for B_s mixing



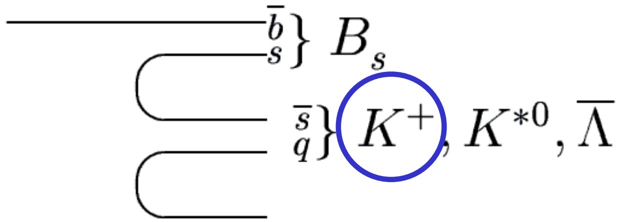


SSKT at CDF

- Systematic studies cover
  - quark fragmentation model
  - $b\bar{b}$ production mechanisms
  - excited *B* mesons content
  - detector / PID resolution
  - particle species content around *B*
  - data / MC agreement



- Select track within $\Delta R < 0.7$ around *B* most likely to be a kaon
  - based on dE/dx and TOF information



CDF *MC 355 pb^{-1}*

$$\varepsilon D^2_{SSKT}\left(B_s^0 \to D_s^- \pi^+\right) = 4.0^{+0.8}_{-1.2}\ \%$$

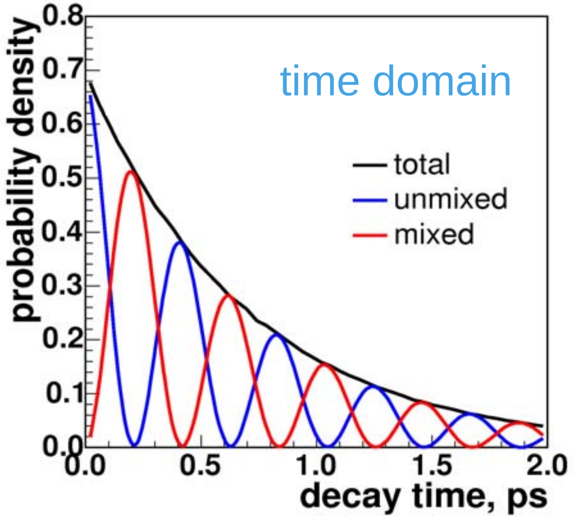
B Mixing Fourier Analysis

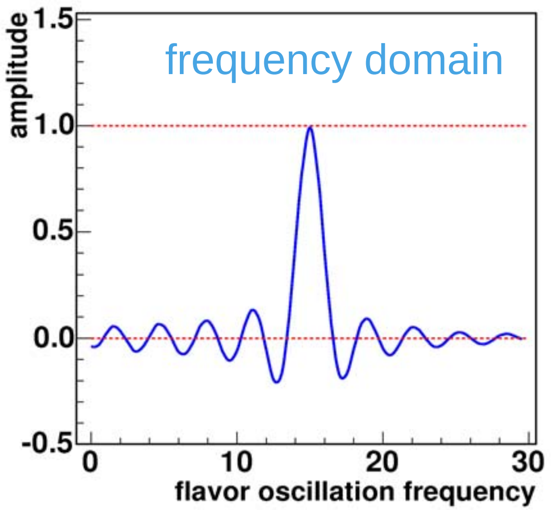
- Two domains to fit for oscillations
  - time $\rightarrow$ fit for a cosine wave
  - frequency $\rightarrow$ examine f-spectrum

- Time domain approach
  - fit for Δm_s in $P(t) \sim 1 \pm \mathcal{D}\cos(\Delta m_s t)$

- Frequency domain approach
  - introduce amplitude, $P(t) \sim 1 \pm \mathcal{A}\mathcal{D}\cos(\Delta m_s t)$
  - fit for $\mathcal{A}$ at different Δm_s

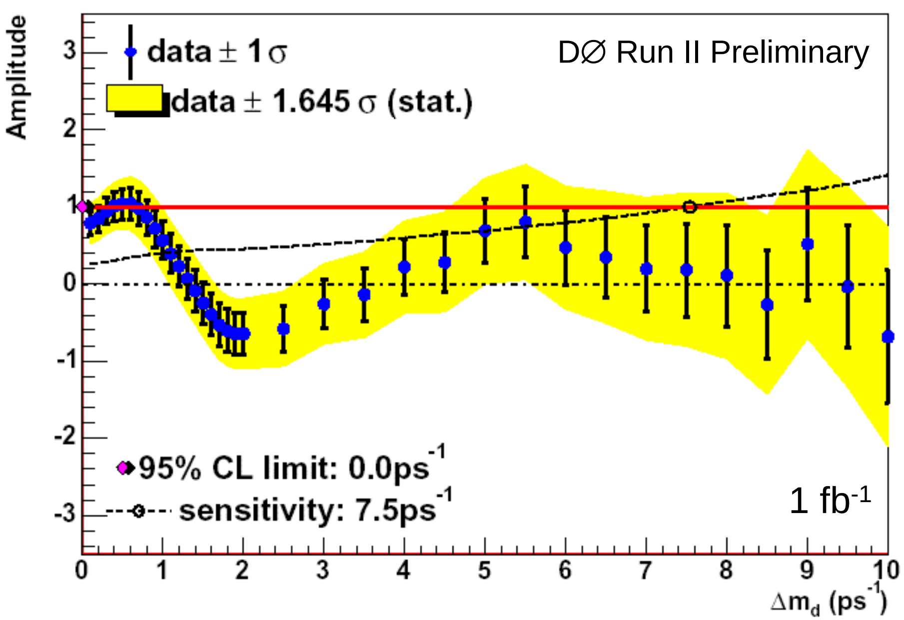
  $\Rightarrow$ obtain frequency spectrum $\mathcal{A}(\Delta m_s)$
  - standard method for combining limits
  - with flavor taggers calibrated $\mathcal{A} = 1$ for the true Δm_s else $\mathcal{A} = 0$



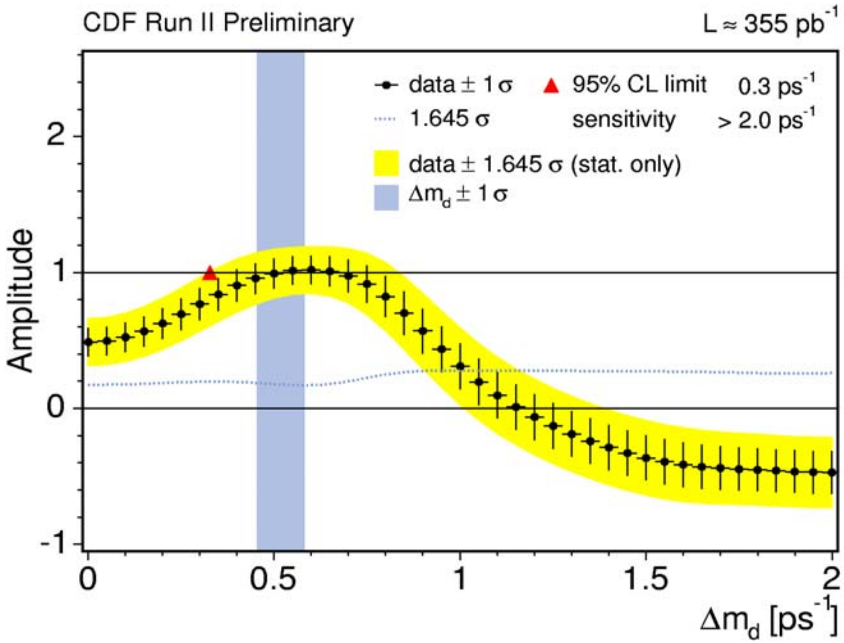


Amplitude Scans on Δm_d

- The yellow band is $\pm 1.645\sigma_{\mathcal{A}}$ around data points
- Δm values where $\mathcal{A} + 1.645\sigma_{\mathcal{A}} < 1$ are excluded at 95% CL
- Sensitivity is where $1.645\sigma_{\mathcal{A}} = 1$



$B \to \mu^+ D^- X$



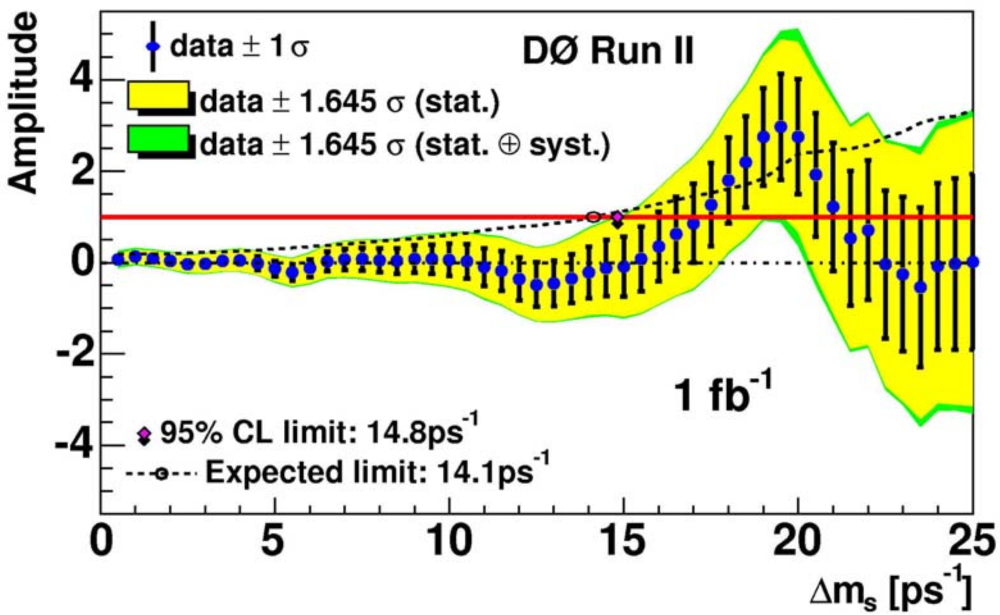
$B^0 \to J/\psi K^{*0}, B^0 \to D^- \pi^+$

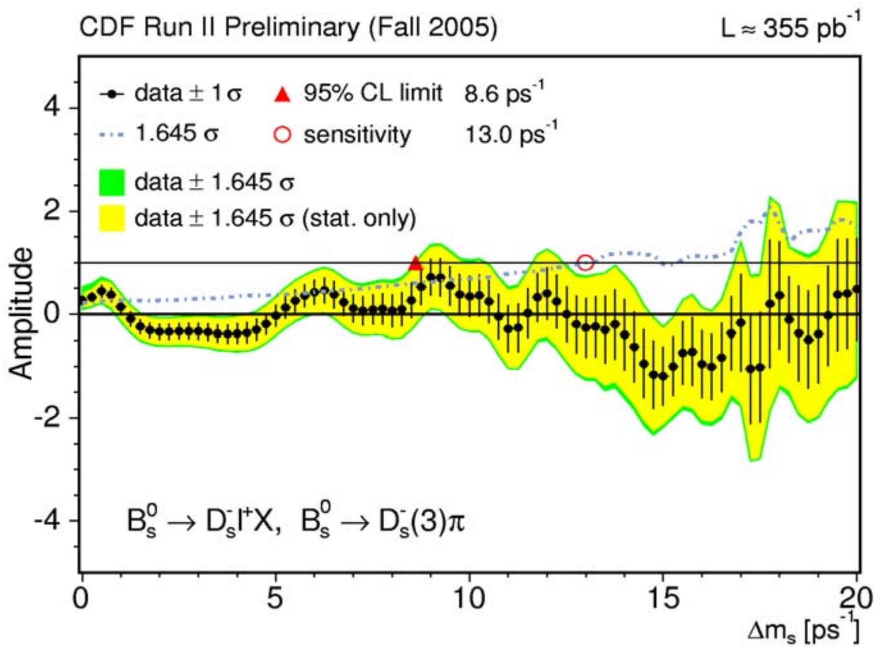
Amplitude scan works on B^0 decay modes

B Mixing Amplitude Scans on Δm_s

$\mathcal{A}/\sigma_{\mathcal{A}}(\Delta m_s = 19\ \mathrm{ps}^{-1}) = 2.5 \Rightarrow 5\%\ p$-value

SSKT not yet included





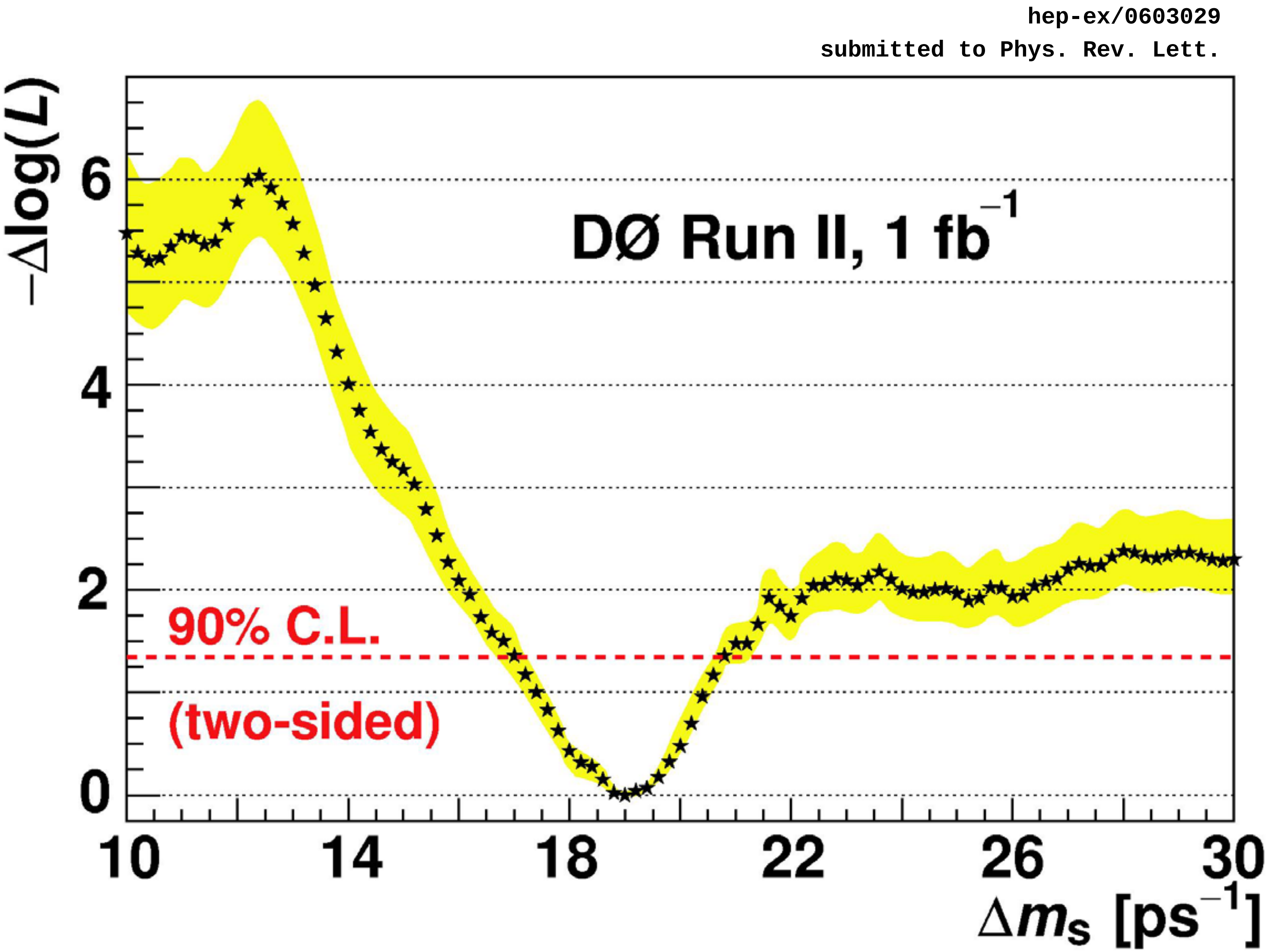
DØ *1 fb^{-1}*

95% CL limit	14.8 ps^{-1}
sensitivity	14.1 ps^{-1}

CDF *355 pb^{-1}*

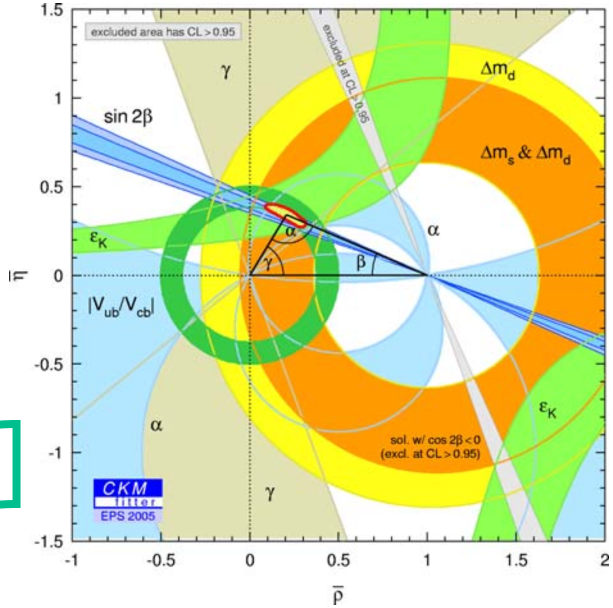
95% CL limit	8.6 ps^{-1}
sensitivity	13.0 ps^{-1}

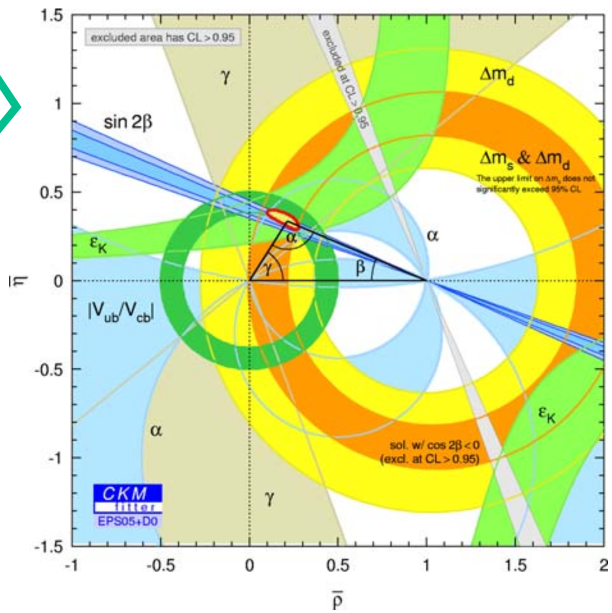
B Mixing Log Likelihood Scan

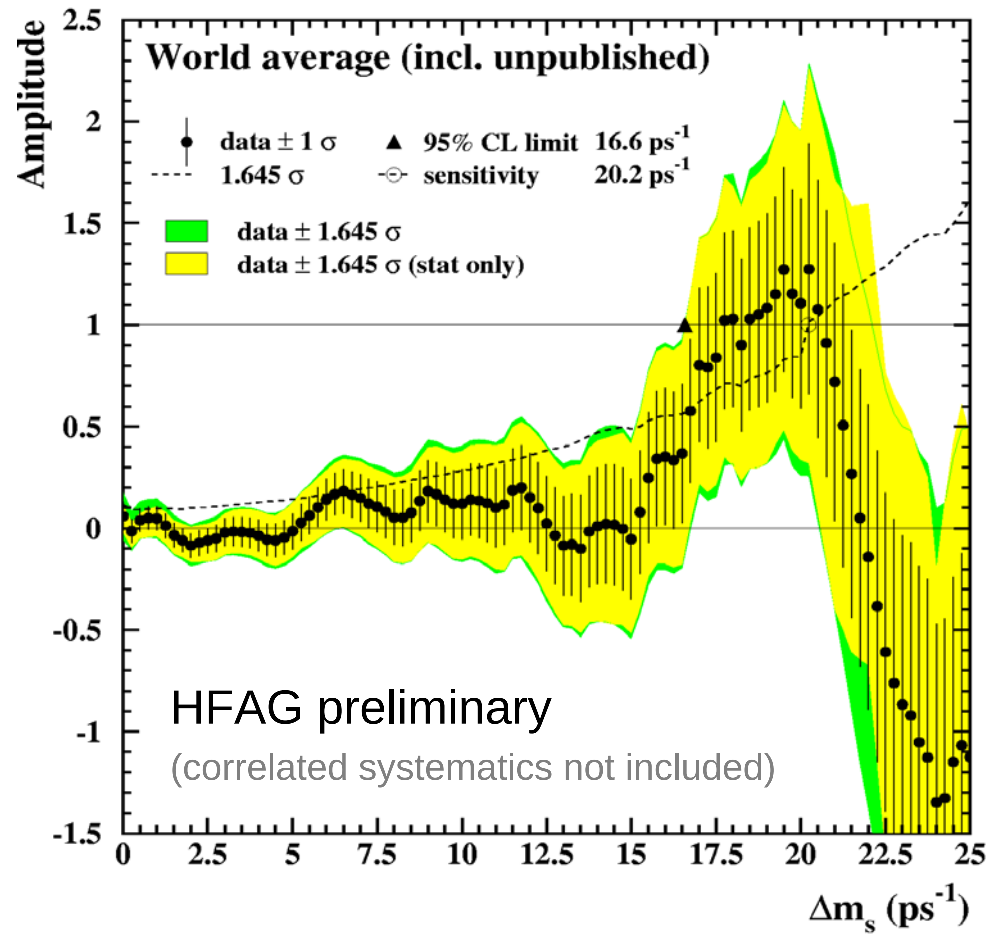


- $17 < \Delta m_s < 21$ ps^{-1} @ 90% CL assuming Gaussian uncertainties

B Mixing DØ Effect on World Average







$\mathcal{A}(\Delta m_s = 19\ \text{ps}^{-1})$

$1.5\ \sigma_{\mathcal{A}}$ $\xrightarrow{\text{DØ}}$ $2.3\ \sigma_{\mathcal{A}}$

Summary

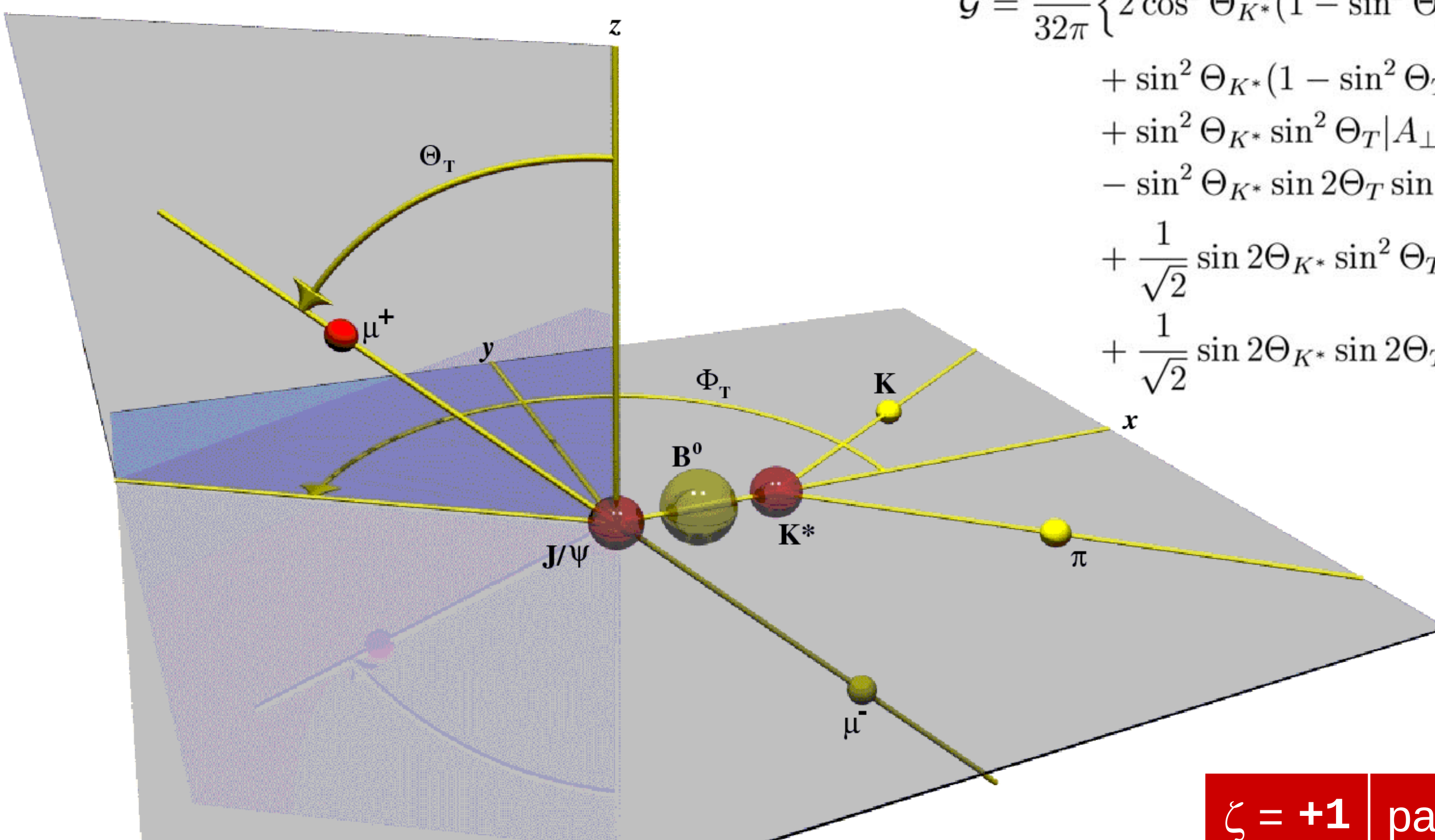
- New Λ_b lifetimes reduce distance with theory
- Tevatron measures the best B_s lifetimes in the world
- B_s lifetime difference within SM

- DØ B_s oscillation
  - 1 fb^{-1}
  - 2.5 $\sigma_{\mathcal{A}}$ excess at $\Delta m_s = 19$ ps^{-1} (5% p-value)
  - $17.1 < \Delta m_s < 21.1$ ps^{-1} @ 90% CL
- CDF B_s oscillation
  - 355 pb^{-1}
  - $\Delta m_s > 8.6$ ps $^{-1}$ @ 95% CL


Backup

Transversity Basis

$$
\begin{aligned}
\mathcal{G} = \frac{9}{32\pi}\Big\{ & 2\cos^2\Theta_{K^*}(1-\sin^2\Theta_T\cos^2\Phi_T)|A_0|^2 \\
&+ \sin^2\Theta_{K^*}(1-\sin^2\Theta_T\sin^2\Phi_T)|A_{||}|^2 \\
&+ \sin^2\Theta_{K^*}\sin^2\Theta_T|A_\perp|^2 \\
&- \sin^2\Theta_{K^*}\sin 2\Theta_T\sin\Phi_T Im(A_{||}^* A_\perp)\zeta \\
&+ \frac{1}{\sqrt{2}}\sin 2\Theta_{K^*}\sin^2\Theta_T\sin 2\Phi_T Re(A_0^* A_{||}) \\
&+ \frac{1}{\sqrt{2}}\sin 2\Theta_{K^*}\sin 2\Theta_T\cos\Phi_T Im(A_0^* A_\perp)\zeta\Big\}
\end{aligned}
$$



ζ = **+1**	particle
ζ = **-1**	antiparticle
ζ = **0**	untagged B_s

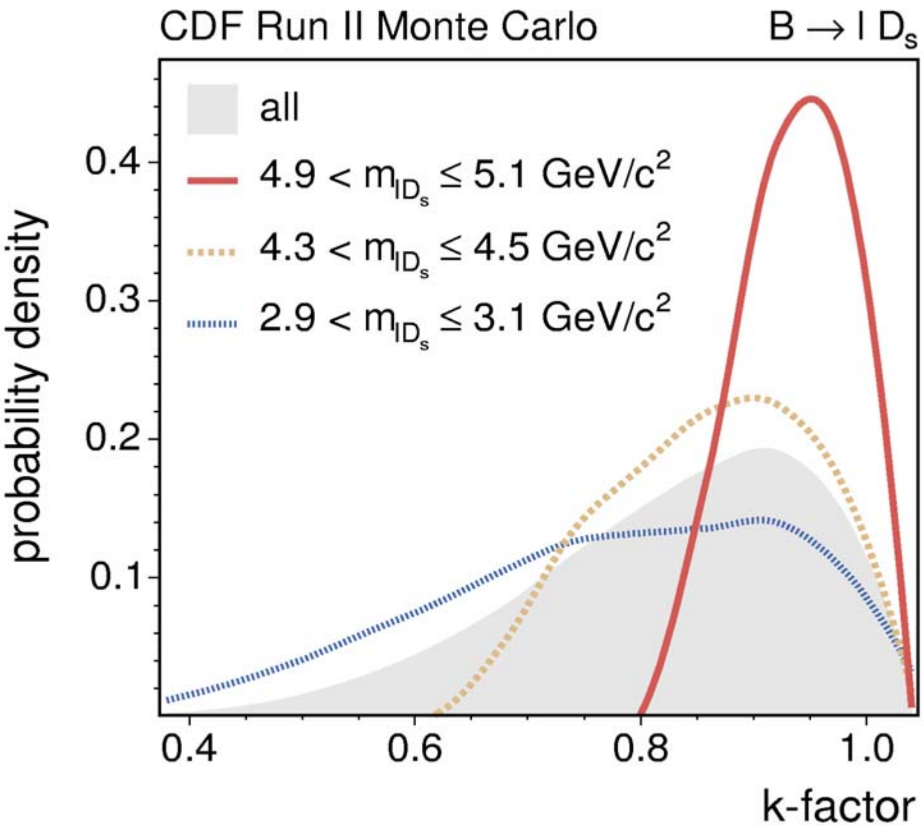
- Transversity basis ≡ J/ψ rest frame
- ϕ flight direction ≡ $+x$
- KK plane ≡ xy plane

Semileptonic Decay Time

- Missing particles ⇒ missing p_T
- Determine pseudo-ct from data

$$ct^* = L_{xy} \frac{m_B}{p_T^{lD}}$$

- $ct = ct^* k_{MC}$
  - include k_{MC} effect in signal PDF



$$P(ct^*) = \frac{k_{MC}}{2c\tau} exp\left(-\frac{ct^* k_{MC}}{c\tau}\right)\theta(ct^*) \otimes Gauss \otimes F(k_{MC})\,\xi(ct^*)$$